Using a smartphone on the move: do visual constraints explain why we slow walking speed?

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Abstract

Viewing one's smartphone whilst walking commonly leads to a slowing of walking. Slowing walking-speed may occur because of safety concerns or because of visual constraints. We determine how walking-induced phone motion affects the ability to read on-screen information.

Phone-reading performance (PRP) was assessed whilst participants walked on a treadmill at various speeds. The fastest speed was repeated, wearing an elbow-brace (Braced) or with the phone mounted stationary (Fixed). An audible cue ('text-alert'), indicated participants had 2 seconds to lift/view the phone and read aloud a series of digits. PRP was the number of digits read correctly. Each condition was repeated 5 times. 3D-motion analyses determined phone-motion relative to the head, from which the variability in acceleration in viewing distance, and in the gaze angles in the up-down and right-left directions were assessed.

A main-effect of condition indicated PRP decreased with walking speed; particularly so for the Braced and Fixed conditions ($p=0.022$). Walking condition also affected the phone's relative motion ($p<0.001$); post-hoc analysis indicated that acceleration variability for the Fast, Fixed and Braced conditions were increased compared to that for slow and customary speed walking ($p\leq 0.05$). Significant negative correlations between phone acceleration variability and PRP were evident ($r\leq -0.16$; $p\leq 0.03$).

These findings may explain why walking speed slows when viewing a hand-held phone: at slower speeds, head-motion is smoother/more regular, enabling the motion of the phone to be coupled with head-motion, thus making fewer demands on the oculomotor system. Good coupling ensures that the retinal image is stable enough to be legible.

Keywords

Smart-phone; Reading performance; Head motion; Vision; Walking.

Introduction

The worldwide rate of smartphone usage is enormous and continues to increase annually, from an estimated 2.5 billion users in 2016 to 3.2 billion users in 2019 (www.statista.com/statistics/330695/number-of-smartphone-users-worldwide). It is very common to see people using their smartphone whilst they move about the environment. There is considerable previous research investigating the effects on walking of concurrently using a smartphone (while reading, texting or talking, Schabrun et al. 2014; Kao et al. 2015; Alsaleh et al. 2018; Crowley et al. 2016, 2019). The findings from these studies show that key walking parameters change as a consequence of concurrent smartphone usage, including having a reduced walking speed with a shortened and wider step. Using a phone whilst walking represents a cognitive dual task, the execution of which has been shown to indirectly affect walking speed (Crowley et al. 2016; Krasovsky et al. 2017) and this could explain why walking speed slows when using a smartphone. It is also possible however, that phone users make a decision, consciously or sub-consciously, to slow walking speed when viewing their screens because of an awareness of an increased risk of tripping over, or colliding with, obstacles in the environment. The evidence that using a smartphone whilst walking causes an increased tripping risk is consistent with findings showing that injuries are more common among pedestrians using a phone compared to pedestrians not using a phone (Nasar and Troyer 2013).

While the effects of smartphone use on walking have been studied, there is currently a paucity of research investigating how the act of walking might affect the ability to use a smartphone, for example, the ability to read the text presented on the screen. The current study is concerned with the impact of walking on the ability to accurately read information presented on the screen of a smartphone.

Reading from a smartphone screen represents one example of a dynamic visual task. Previous studies of vision under dynamic conditions have typically determined the smallest letter/symbol size that can be resolved, when either the target being viewed is in motion whilst the participant is static (Ludvigh and Miller 1958; Miller 1958), or when the participant's head is rotating whilst viewing a static target (Roberts et al. 2006; Vital et al. 2010). Findings from these studies indicate that, although a certain amount of target and/or head motion can be tolerated without a detrimental effect on visual acuity (Westheimer and McKee 1975), in general visual acuity decays as a function of increasing speed of target or of head rotation (Ludvigh and Miller 1958; Miller 1958, Roberts et al. 2006; Vital et al. 2010, Westheimer and McKee 1975). A disadvantage of these approaches in assessing dynamic vision is that they do not reflect the dynamic conditions where both the individual and the target being viewed are in motion. These dynamic situations represent a complicated visual challenge and one such situation is viewing information on a hand-held smartphone while the user is concurrently walking. In this situation both the head and phone are in motion.

When walking, the motion of the head can be described as rhythmic, with the extent and frequency related to the walking speed (Verbecque et al. 2018), and with higher walking speeds inducing increased motion with a more variable head-acceleration pattern (Latt et al. 2008). Walking induces not only head motion, but also motion of the freely swinging arms, meaning that motion of a handheld phone will be different to that of the head and hence the eyes. The motion of the phone relative to the eyes will create varying demands of the gaze-control systems in order to stabilise the retinal image of the information presented on the smartphone screen. Holding a phone while walking will also mean that the distance (in depth direction) between the phone and the eyes will vary (Schabrun et al. 2014). As well as moving, this variation in depth may prompt the need for greater and lesser amounts of accommodation, as the phone-to-eyes distance reduces and increases, respectively. Depending on the size of the detail being viewed, not being able to adjust to changes in the accommodative demand quickly enough as the phone moves (in depth direction) could cause the information on the screen to appear out of focus.

Having a stable, or a relatively stable, retinal image is also important for achieving good visual performance. When retinal image motion (horizontal or vertical) is greater than 2.5 degrees/second, the ability to discriminate fine detail decays (Westheimer and McKee 1975). When viewing a stationary object while the head is moving, the vestibular-ocular reflex (VOR) triggers compensatory eye movement in the opposite direction to stabilise the retinal image (Leigh and Zee 1999). However, whilst walking and viewing a smartphone, stabilising the retinal image will likely require additional eye movements to those induced by the VOR alone. The need to stabilise the retinal image of the screen can be reduced by coupling the motion of the phone to the motion of the head. Such coupling represents another mechanism a walker can use to ensure that the information presented on the phone screen is stabilised and thus can be seen clearly. Motion-coupling arises when the movements of two body segments are co-ordinated within an overall movement pattern (Donker et al. 2001; Garg et al. 2014; Hamill et al. 2020). Hence if the motion of the hand-held phone is coupled with the walking-induced motion of the head, this would minimise the extent to which VOR and pursuit eye movements are needed. A drive to couple the motion of the phone to motion of the eyes, in order to minimize the eye movements that would otherwise be required, could also explain why pedestrians slow their speed when viewing the screen on their smartphone.

Previous research investigating dynamic visual acuity (DVA) whilst reading a smartphone when walking has reported that reducing the phone-to-eyes distance, or increasing the size of the text/numbers helps to compensate for the reduction in visual acuity that is induced by walking (either overground or on a treadmill), but reducing walking speed by itself did not improve DVA (Conradi and Alexander 2014). In a study undertaken in the Nokia Research Centre, phone-text legibility was shown to be affected by speed of walking, with improved legibility at slower speeds (Mustonen et al. 2004). However, the latter study provided no insights as to why phone-text legibility was better at slower speeds.

The aim of the present study was to determine how increases in the phone-to-eyes relative motion during walking might affect the ability to read information displayed on a smartphone. The approach we take here is to measure smartphone reading performance when the motion of the phone relative to the eyes is modulated. This was achieved in two ways: (a) by gradually increasing the walking speed which induced increased head and hand (phone) motion, and (b) walking whilst wearing an elbow brace or walking with the phone mounted on the treadmill (static), which restricted or eliminated, respectively, the ability to couple the movement of the hand-held phone with the motion of the eyes.

We hypothesised that, because head motion would be relatively low and regular when walking at slow and customary speeds, participants would be able to achieve good coupling between the motion of the hand-held phone and motion of the eyes, i.e., phone-to-eyes relative motion would be relatively smooth and regular, so that reading information from the screen would be achieved with similar ability as when standing still. However, with faster walking, particularly when wearing an elbow brace or having a stationary phone, it would be difficult, or impossible, to achieve good coupling between the motion of the phone and motion of the eyes, and thus phone-to-eyes relative motion would become erratic, resulting in substantial decrements in reading performance. With erratic phone-to-eyes relative motion, the decrements in reading performance would result from an inability to make the necessary eye movements and/or adjustments in accommodation to achieve a sufficiently stable and focussed retinal image for the task to be effectively executed.

Materials and methods

Participants

Twenty healthy individuals (10 males, 10 females; 25.1 ± 4.3 years; height, 1.7 ± 0.1 m; mass, 71.6 ± 22.1 kg) took part in the study. Participants were excluded if they were older than 35 years, had consumed alcohol in the last 24 h, had any injury or musculoskeletal disorder or were taking medicines that might affect gait, balance or posture. They were also excluded if their visual acuity of either eye (assessed with the Snellen chart, MacLure 1980, Clement Clarke International Ltd. - London, UK) with the refractive correction habitually worn outdoors (either single-vison spectacles or contact lenses) was worse than 6/9 (0.18 LogMAR) at distance (6 m) or near (35 cm), or if stereoacuity was worse than 100" of arc. Stereoacuity was assessed at 40 cm using the "Random dot" test (Stereo Optical Co. Inc., Chicago, IL, EEUU). All participants owned a smartphone and indicated they regularly used it whilst walking. Motor eye dominance was determined using the Dolman method (hole-in-the-card test, Fink 1938). Sixteen participants (80%) were found to be right eye dominant and four were left eye dominant.

Ethical approval was obtained from the University of Bradford's Committee for Ethics in Research and the tenets of the Declaration of Helsinki were followed. All participants gave informed and written consent prior to data collection.

Experimental protocol

Participants were asked to attend the laboratory wearing shoes and clothes appropriate and comfortable for walking.

Each participant was first familiarised with walking on the laboratory treadmill (M-mill, ForceLink - Culemborg, The Netherlands) for a period of 2-5 mins. Each participant's customary walking speed was then determined using the approach described by Jordan et al. (2007). The treadmill was started and participants began walking. The belt speed was then incrementally increased until the participant indicated it was their "normal" walking speed. The treadmill speed was then increased further to a noticeably fast speed (from the participant's perspective), after which it was incrementally decreased until, once again, the participant indicated the speed was "normal" for them. The average of the two recorded values was taken as the participant's customary speed (*Cust*).

Phone reading task

An automated presentation simulating how one of the most widely used chat-apps displays text on a phone-screen (i.e., a WhatsApp® chat) was created for use on a smartphone (iPhone 7 - Apple Inc., Cupertino, CA, EEUU). The presentation was an array of 11 single-digit numbers displayed in random order, in the format of a UK-style phone number (5 digits - space - 6 digits, e.g., 79564 348967) and using a font type and size frequently used in iOS (Helvetica Neue, 38 pt., requiring a visual acuity of 6/24 or better based on a 30-35cm viewing distance). Fig. 1a shows how each trial was run.

When participants were on the treadmill, they were asked to hold the phone in their preferred hand (right hand for all 20 participants) with the arms relaxed and free to swing, as in normal walking. Participants were asked to look to their front until a phone "beep" (lasting 750 ms) was heard, simulating the situation in which a “new message” had been received. On hearing the beep, participants were asked to lift the phone and to view the screen (Fig. 1a).

The visual stimulus appeared one second after the “beep” started and remained on the screen for 2 seconds. Presentation timings were checked using an oscilloscope during pilot work and were found to be accurate within ± 20 ms of the intended 2-second duration. Screen brightness was set at 100%. The phone was turned to “do not disturb” mode to avoid possible distractions (other notifications, calls, etc.).

Participants were asked to read aloud and in sequence (from left to right) the numbers that appeared on the screen. They were instructed to speak loudly enough so that they could be heard by the researcher. They were asked to name each digit separately, for example saying “one-two” rather than “twelve”, or “zero-zero” rather than “double-zero”. No more than 3 repeated digits were displayed in any one “message”. Once the stimulus disappeared from the screen, participants were instructed to return their arms to their sides (as in normal walking), and to once again direct their gaze frontwards. After 5 seconds, the next reading trial commenced until a block of 5 trials had been completed.

Participants undertook a block of 5 practice trials whilst walking at their customary walking speed. The phone reading task was then completed for the following six conditions in a pseudo-random order: standing still (*Standing*), walking at customary speed (*Cust*), walking at 80% of customary speed (*Slow*), walking at 130% of customary speed (*Fast*), walking at the fast speed whilst wearing an elbow-brace on the right arm (ROM Elbow Brace; Praxis Medical Ltd., Brierfield, Lancashire, UK) with the angle at the elbow set at 105 degrees (*Braced*), and walking at the fast speed with the phone mounted in a static position (i.e., not hand-held) in front of the participant, at their preferred distance (typically 40 cm away from the participant) (*Fixed*).

Phone reading performance (PRP) was recorded using a sheet showing the correct set of numbers for every condition and trial. As the participant called out the numbers, the researcher recorded each correctly named digit. The total number of digits (out of 11) correctly read was the PRP for that trial. If a digit was missed from the sequence or misread but the remaining numbers were read correctly, this was recorded as a single-digit mistake; such errors were very infrequent (<1% of trials). Decrements in PRP were invariably due to failing to read the numbers in the latter part of the sequence (due to running out of time) rather than reading out an incorrect number.

Kinematic (motion) analysis

Infrared, reflective markers were attached to the head, via a headband. The markers were placed approximately over the left and right temples, and over the left and right posterolateral aspects of the head (Fig. 1b). Three infrared markers were also attached to a plastic card fixed to the phone (Fig. 1b). A six-camera motion analysis system (Vicon Bonita, Oxford Metrics PLC, Oxford, UK) was used to track and record marker motion in 3D space (at 100 Hz) as participants first completed a static calibration trial followed by each of the six conditions described above. The static calibration trial was recorded with each participant standing still whilst looking at a marker placed 1.5m in front of them. This marker was horizontally and vertically aligned with the midpoint of their eyes when the head and eyes were directed straight ahead (neutral head and gaze position).

The motion data files collected from each participant, including static calibration, were post-processed using the Nexus 2.8 software in the following manner. Markers were reconstructed and labelled, and any gaps in their trajectories were filled. Data were then filtered using a low-pass digital filter (Butterworth) with a cutoff frequency of 6 Hz. The four head markers were joined to form a “head” segment, and the three markers attached to the phone formed a “phone” segment.

Determination of phone motion relative to the head

Setting the head-segment reference frame at the eyes' midpoint

From the data collected for the static calibration, we set the origin of the head-segment's reference frame (axes) at the midpoint of the eyes by undertaking the following steps within the ProCalc software. From the midpoint of the two front head markers, a vertical line was projected 4 cm down to the nasal bridge: pilot work had indicated that 4 ± 0.5 cm was typical for the eye-plane location relative to the headband. A horizontal offset of 1 cm towards the back of the head was then applied to match the approximated depth in the skull where the eyes are located. A virtual marker (*Eyes*) was then created at this location. The head's reference frame (origin of axes) was embeded at the *Eyes* (Fig. 1b) with its axes rotated to match the "neutral gaze angles" for the static calibration position (see Online Resource 1). Once embeded for this neutral position, the reference frame would obviously move when the head moved, i.e., in the dynamic trials.

A virtual marker (*Screen*) representing the position of the midpoint of the stimuli on the screen was also created. The location of this point was determined by measuring its distance from the "phone" segment markers (Fig. 1b).

Fig. 1 near here

Assessing gaze without tracking eye movements

To measure gaze angle changes for each participant, we assumed that when they were reading the digits on the phone, their gaze was directed at the midpoint of where the digits were displayed. Thus, by tracking the movement of the phone in the head-segment's reference frame (i.e., relative to its position when gaze was "neutral"), the angular changes in assumed gaze that occurred during the phone reading period were measured. We assumed that during the period when the participant was reading the numbers, any relative movement of the *Screen* in the head's *x-z* plane (Fig. 1c) would mean that gaze must have been shifted leftwards or rightwards from neutral. Similarly, any relative movement of the *Screen* in the head's *y-z* plane (Fig. 1c) must have meant gaze shifted upwards or downwards from neutral. In other words, by knowing that participants had to be directing their gaze to the phone screen in order to read the text presented on it, any up-down or right-left motion of the phone relative to the head during this period was assumed to cause a redirection of gaze (i.e., changes in the assumed gaze angle in right-left and up-down directions).

Determination of phone reading period

The phone reading period was determined as the instant at which the motion of the phone was 'stable' after raising it in order to read the digits displayed on the screen. This was determined using the following procedure. The first derivative of the phone's relative displacement (relative to the head) in the vertical direction was determined (phone relative vertical velocity, *z* axis) (Fig. 2a). The local maximum in the relative velocity (peak/zenith) was then located and an offset of 50 ms was added. The resulting time-point was considered as 'stability' onset. The 50 ms offset was included following pilot work which indicated the phone's relative vertical velocity had reduced to near-zero after 50 m/s or less following the local maxima. Outcome measures that described how the phone was moving relative to the head were determined for only the period from 'stability' onset up to 2 seconds later, i.e., the period when the digits to be read were displayed on the screen.

For the *Fixed* phone condition, participants did not hold the phone so the method described above to determine each trial's 'stability' onset could not be used. Instead, participants were asked to touch their right shoulder with their right hand when they heard the phone "beep". Touching their shoulder simulated the "phone-lifting" that occurred in the other conditions. For these trials, an extra marker was placed on their right hand. By analysing the motion of this marker, a similar procedure to that described above was applied to find the test onset (comparable to 'stability' onset) for this condition.

Kinematic outcome measures determined for phone reading period

- Viewing distance (D_{RES}). Determined as the resultant linear displacement of the *Screen* relative to the *Eyes* position (Fig. 1c) using the formula:

$$D_{RES} = \sqrt{{D_x}^2 + {D_y}^2 + {D_z}^2}$$

where Dx, Dy, and Dz indicate the relative phone displacement in the X, Y, and Z directions.

As viewing distance was continually changing during the reading period, we also determined the velocity (D_{RES}_Vel) and acceleration (D_{RES}_Acc) of changes in viewing distance.

- Right-left and up-down assumed gaze angles (RL_{GAZE}, UD_{GAZE}).

As described above (see *"Assessing gaze without eye-tracking"*), any up-down or right-left motion of the phone relative to the head was assumed to cause a redirection of gaze angle in right-left and up-down directions, respectively (Fig. 1c). Therefore, the assumed gaze angles were determined in degrees using the following formulae:

$$UD_{GAZE} = \tan^{-1}\frac{D_Z}{D_y} \cdot (180/\pi)$$

$$RL_{GAZE} = \tan^{-1}\frac{D_x}{D_y} \cdot (180/\pi)$$

where Dx, Dy, and Dz indicate the relative phone displacement in the X, Y, and Z directions, respectively.

As gaze direction was dynamically changing during the reading period, we also determined the angular velocity (UD_{GAZE}_Vel, RL_{GAZE}_Vel) and acceleration (UD_{GAZE}_Acc, RL_{GAZE}_Acc) of the assumed gaze angle changes.

Statistical analysis

To change the motion of an object requires application of a force, which causes the object to accelerate. This means that changes in the acceleration of object precedes changes in the object's displacement and velocity. This explains why perturbations in acceleration have been widely used to analyse how the act of walking affects dynamic stability (Menz et al. 2003; Kavanagh et al. 2004, 2005; Latt et al. 2008). In the current study our statistical analysis focuses on determining if, or how, the phone's acceleration relative to the eyes differed across the different conditions. To this end, we determined the variability in the phone's relative acceleration (relative to the head). Variability was determined as the standard deviation (SD) of the fluctuations in acceleration of the resultant phone-to-head distance (D_{RES}_Acc-SD), and in the Up-Down (UD_{GAZE}_Acc-SD) and Right-Left (RL_{GAZE}_Acc-SD) assumed gaze angles for each phone reading period.

For descriptive purposes we also determined the group mean (± SD) phone-to-eyes distance, and the mean Up-Down (UD) and Right-Left (RL) gaze angles.

To determine if outcome measures differed across conditions, data were analysed using repeated measures ANOVA, with condition and repetition as repeated measures factors. We used JASP (University of Amsterdam, Amsterdam, The Netherlands) for statistical analysis. The same software was used to undertake Holm-corrected post-hoc analyses. As a null hypothesis procedure, p-values below 0.05 were considered as statistically significant. Sphericity tests were performed and when necessary, a Greenhouse-Geisser correction was applied to correct the degrees of freedom. Thus, all the p values shown have been corrected where the assumption of sphericity was violated.

For any of the outcome measure that were found to differ significantly across conditions, we determined how the changes in that outcome measure were associated with PRP. This was performed using repeated measures correlation analysis ("RmCorr", Bakdash and Marusich 2017) using RStudio (RStudio Inc., Boston, MA, EEUU).

Across the participant group PRP was seen to, in general, improve from trial one to four but was consistently poorer in the 5th trial compared with the previous 4 repetitions (i.e., on average there was at least one more reading mistake in trial 5 compared to all other trials). As participants were completing the reading task on the 5th trial, the word "Finished!" appeared. Although the digits to be read had disappeared when this word appeared on the screen, the ability to complete the reading task on the 5th trial was believed to be impaired by the presentation of this text after the disappearance of the digits. This unanticipated finding suggested a systematic error that likely made participants lose their focus on the task. Therefore, data from the 5th trial of every condition for all participants were excluded from the analyses.

Results

The group average positioning of the phone relative to the eyes during the phone-reading period, and the associated assumed gaze angles for the different testing conditions are shown in Table 1. Values in the first column (D_{RES}) show the group mean distance (± SD) of the phone relative to the eyes. Values in the second and third columns show the group average mean (± SD) assumed gaze angles (UD_{GAZE} and RL_{GAZE}) in the Up-Down and Right-Left directions, respectively. There was a main effect of condition found for average viewing distances (D_{RES}; $p<0.001$). Post-hoc follow-up indicated that D_{RES} for the *Braced* and *Fixed* conditions were significantly greater than all other conditions ($p < 0.001$), and that D_{RES} for the *Fixed* condition was significantly greater than for the *Braced* condition ($p < 0.001$). There was also a main effect of condition for the average gaze angle in the right-left direction (RL_{GAZE}; $p=0.009$), and post-hoc analysis indicated that RL_{GAZE} for the *Braced* condition was significantly greater than all other conditions accept *Fixed*. There were no significant main effects for condition in the average up-down gaze angle ($p = 0.557$).

Table 1 near here

Fig. 2b presents exemplar data from one participant showing the phone's relative motion during a trial at customary walking speed. We focussed our statistical analysis on investigating how the phone's acceleration relative to the eyes differed across the different walking conditions. This is because we knew that changes in the phone's relative acceleration would precede any changes occurring in its relative velocity or displacement. Fig. 2b highlights the merits of focussing on investigating changes in the phone's relative acceleration, i.e., it highlights that the fluctuations for the acceleration trajectory are more evident than those occurring in either the velocity or displacement trajectories.

Fig. 2 near here

Phone Reading Performance (PRP)

Group average PRP across each of the six conditions is shown in Fig. 3a. The figure highlights how PRP decreased with increased walking speed, and it decreased further for the *Fixed* condition and further still for the *Braced* condition. There was a significant main effect for condition ($p = 0.022$) and trial repetition ($p = 0.015$), but there was no interaction between terms ($p = 0.318$). The condition main effect indicated that PRP tended to become poorer at the fastest speed, particularly for the *Fixed* and *Braced* conditions, and post hoc analysis indicated PRP in the *Braced* condition was significantly poorer compared to the *Standing* ($p = 0.016$) and the *Slow* ($p = 0.013$) conditions. None of the differences between the other conditions reached statistical significance (all $p>0.6$). Post-hoc analysis indicated the average PRP achieved in the first trial was significantly poorer compared to the third ($p = 0.021$), suggesting a training effect in the task. However, PRP did not differ between any of the other trial repetitions.

Fig. 3 near here

Effects of phone to head relative acceleration

Group average trial acceleration variability in the resultant phone-to-eyes distance (D_{RES}_Acc-SD), and in the Up-Down (UD_{GAZE}_Acc-SD) and Right-Left (RL_{GAZE}_Acc-SD) assumed gaze angles across the different conditions, are shown in Fig. 3b-d. Similar trends across the different testing conditions were found for group average velocity variability and group average displacement variability in the resultant phone-to-eyes distance (D_{RES}_Acc-SD) and in the Up-Down (UD_{GAZE}_Acc-SD) and Right-Left (RL_{GAZE}_Acc-SD) assumed gaze angles (see Online Resource 2).

There were main effects of condition for all outcome variables (D_{RES}_Acc-SD; UD_{GAZE}_Acc-SD; RL_{GAZE}_Acc-SD, $p<0.001$), but there was no effect of repetition ($p > 0.149$) and no interactions between terms ($p > 0.365$). The condition main effect indicated D_{RES}_Acc-SD increased with walking speed and increased further in the *Fixed* condition, and further still in the *Braced* condition (Fig. 3b). UD_{GAZE}_Acc-SD and RL_{GAZE}_Acc-SD also increased across the conditions from *Standing* to *Fixed*, but was seen to reduce slightly for the *Braced* compared to the *Fixed* condition (Fig. 3b). Post-hoc analysis indicated that the variability in acceleration outcomes (D_{RES}_Acc-SD, UD_{GAZE}_Acc-SD, RL_{GAZE}_Acc-SD) for the *Standing* condition were significantly reduced compared to all the other conditions ($p < 0.001$) and that D_{RES}_Acc-SD for the *Fast*, *Fixed* and *Braced* conditions were significantly increased compared to *Slow*, and *Cust* conditions ($p < 0.029$). Also, UD_{GAZE}_Acc-SD for the *Fast* and *Fixed* conditions was significantly increased compared to *Slow*, and *Cust* conditions ($p \leq 0.05$). In addition, RL_{GAZE}_Acc-SD for the *Fast*, *Fixed* and *Braced* conditions was significantly increased compared to *Slow* condition ($p \leq 0.007$).

Association between Phone Reading Performance and kinematic outcomes

D_{RES}_Acc-SD, UD_{GAZE}_Acc-SD, RL_{GAZE}_Acc-SD were, in general, found to increase across conditions (from *Standing* to *Braced*, Fig. 3b-d), whilst PRP was found to decrease across the conditions (Fig. 3a). This suggested there was an association between PRP and the kinematics of the phone relative to the head. Hence, we used repeated measures correlation analyses (Bakdash and Marusich 2017) to determine the degree of association between PRP and each of the variability in acceleration outcome measures.

This analysis indicated a significant negative correlation between D_{RES}_Acc-SD and PRP ($r = -0.16$; $p < 0.0004$, Fig. 4), and between RL_{GAZE}_Acc-SD and PRP ($r = -0.10$; $p = 0.033$). However, the correlation between UD_{GAZE}_Acc-SD and PRP was not statistically significant although it did approach statistical significance ($r = -0.09$; $p = 0.056$).

Fig. 4 near here

Given the significant relationship between PRP and both D_{RES}_Acc-SD and RL_{GAZE}_Acc-SD, and given that the relationship between PRP and UD_{GAZE}_Acc-SD approached being significant, we used regression analyses to explore further the relationship between PRP and each of the variability in acceleration variables (D_{RES}_Acc-SD, UD_{GAZE}_Acc-SD, RL_{GAZE}_Acc-SD). We plotted, as “x, y” scatter graph in Excel, PRP against each acceleration variable using the data from all participants (see Online Resource 2). For these plots we only included the acceleration data collected from the walking conditions (i.e., data collected for the S*tanding* condition were excluded). In each plot, a linear regression model was used in which the regression line intercept (“c” value) was set as the group average PRP value determined for the standing condition (which was 9.06 digits read correctly in the two second time period). This approach allowed us to determine how PRP decreased from the standing condition as acceleration variability increased with increases in walking speed, and with the additional disruption to the motion coupling between the phone and the eyes that took place in the *Braced* and *Fixed* conditions. The resulting linear regression equations for each plot were as follows:

$$\begin{aligned} &D_{RES}\_Acc-SD, && y = -0.0007x + 9.0625 \\ &UD_{GAZE}\_Acc-SD, && y = -0.0021x + 9.0625 \\ &RL_{GAZE}\_Acc-SD, && y = -0.0041x + 9.0625 \end{aligned}$$

These equations model how, on average, PRP decreases as acceleration variability increases. For example, the equation for the UD_{GAZE}_Acc-SD plot, indicates that for every incremental increase in acceleration variability (deg/s^2), PRP would decrease by 0.0021, i.e., PRP would decrease by 0.5 if variability increased by 105 deg/s^2, and PRP would decrease by 1.0 if variability increased by 210 deg/s^2. In contrast, from the equation for the RL_{GAZE}_Acc-SD plot, this indicates that PRP would decrease by 0.5 if variability increased by 205 deg/s^2, and by 1.0 if it increased by 410 deg/s^2. This suggests that a worsening in PRP was associated with larger increases in the variability in acceleration in RL_{GAZE} compared to those in UD_{GAZE}, which suggest visual performance was affected more by eye movements in the right-left direction than in the up-down direction. The equation for the D_{RES}_Acc-SD shows an even smaller constant of 0.0007. However, given that D_{RES}_Acc-SD was measured in mm/s^2 whilst UD_{GAZE}_Acc-SD and RL_{GAZE}_Acc-SD were measured in deg/s^2 it is difficult to make any comparative interpretations regarding how increases in D_{RES}_Acc-SD affected visual performance.

Discussion

The aim of the present study was to determine how walking-induced motion of a hand-held phone in relation to the motion of the eyes, affects the ability to read text (numbers) displayed on the phone. Findings highlight that when walking on a flat and level treadmill at customary and slow speeds, motion of the phone relative to the eyes occurred in a smooth and regular manner (i.e., the phone's acceleration relative to the eyes occurred with low variability), and as a result PRP was as good as it was when standing still. However, at faster walking speeds, and in particular when the elbow of the arm holding the phone was braced or when the phone was mounted stationary on the treadmill, motion of the phone relative to the eyes became irregular. This led to an increase in the variability of the phone's relative acceleration (Fig. 3b-d) and, as a consequence, PRP became significantly poorer (Fig. 3A).

We speculated that a drive to couple the motion of the phone to motion of the eyes (see introduction), in order to minimize the eye movements that would otherwise be required to stabilise the retinal image, may explain why pedestrians slow their speed when reading their phones. The finding that at customary walking speed, relative phone motion was comparatively smooth and regular and PRP was as good as it is standing still, would suggest there is no need to slow customary walking speed to read information presented on a phone. Why then do we see people slowing down as they view their phones? In the present study, participants read their phone whilst walking on a constant-speed and level treadmill. Walking on a treadmill is different to walking overground in a few key respects. Firstly, on a treadmill, there is no requirement to make locomotive adjustments to control heading direction and/or for the avoidance of approaching obstacles. Secondly, the backwards movement of the treadmill belt changes the biomechanical requirements of walking. Both these aspects are likely to make walking more metronomic and thus make motion of the phone relative to the eyes more predictable and thus more regular than that which occurs when walking at the same speed overground. Furthermore, previous research has shown that self-selected "normal" walking speed is slightly slower on a treadmill than in overground walking ($\Delta \approx 0.2$ m/s) (Malatesta et al. 2017), and this speed difference may mean the present study underestimated the impact of customary speed walking on the ability to read information from the screen. We believe that this difference may explain why in the present study there was little effect on PRP at the customary walking speed. The limitations of using a treadmill are discussed further below, along with discussion of all findings from the study. This is one of only a few studies (Mustonen et al. 2004; Barnard et al. 2005; Schildbach and Rukzio 2010; Ng et al. 2014) to investigate how the act of walking impacts on the ability to process visual information presented on a phone screen. Understanding how walking affects the ability to use a phone is important, because the worldwide rate of smartphone usage is enormous (S.O'Dea 2020) and it is extremely common to see people using their phone whilst moving around their environment.

In the present study, determining whether the motion of the phone relative to the eyes was regular or erratic, was achieved by determining the variability in the phone's relative acceleration in the depth direction (i.e., forwards-backwards), and in the up-down and side-to-side directions. Determining the variability in the phone's relative acceleration in the depth direction indicates the variability in viewing distance. The variability in the phone's relative acceleration in the up-down and side-to-side directions, on the other hand, indicate the variability in assumed gaze angle in the up-down and right-left directions, respectively. The findings indicating PRP was poorer when there was increasing variability in the acceleration in viewing distance and in the assumed gaze angle in the up-down and right-left directions, suggest that the visual system could not make the necessary eye movements and/or changes in accommodation quickly enough to stabilize and/or focus the retinal image of the irregularly moving phone. We believe these findings could explain why pedestrians slow their walking when viewing their phones, i.e., they decrease walking speed because the head motion induced at slower speeds is smoother and more regular, which means it is easier to couple the motion of the hand-held phone to motion of the head, hence the retinal image of the phone screen is stable enough and/or clear (in focus) enough to be legible. Related to the above, it is worth noting that the regression line for PRP against RL_{GAZE}_Acc-SD had a gradient of -0.004, whilst the gradients of the lines for the other two plots (PRP against D_{RES}_Acc-SD, PRP against UD_{GAZE}_Acc-SD) were considerably lower at -0.001 and -0.002 respectively (Online Resource 2). This suggests that PRP was affected more by changes in RL_{GAZE} than changes in D_{RES} or UD_{GAZE}, which implies that the visual system can cope with depth (accommodation and vergence) changes and changes in up-down gaze angle better than it copes with changes in right-left gaze angle. Changing viewing distance (i.e., depth) necessitates disjunctive movements (convergence or divergence) of the eyes (Judge 1996), and up-down movements of the phone requires version eye movements. In both cases, the eye-movements required are of a similar magnitude in the two eyes. By contrast, changing the right-left gaze direction will require movement of the eyes in the same direction but by unequal amounts. This is a feature of a translational VOR and it only becomes important when viewing near objects. This requires a greater level of control because the brain must move the eyes independently to keep the image on the fovea of the two eyes (Grossman et al. 1989; Crane et al. 1997; Leigh and Zee 1999). The requirement for unequal eye movements may provide an explanation for why variability of acceleration in the right-left gaze angle was more detrimental to PRP compared to variability of acceleration in the forwards/backwards and up/down planes. However, as we did not set out to directly investigate these aspects this speculative, and thus future work is needed to confirm or refute it.

PRP was poorest for the conditions that had the greatest variability in the phone's relative acceleration, namely the *Braced* and *Fixed* conditions. What factors might explain these findings? One possibility relates to the fact that the average viewing distance for these conditions differed considerably by comparison with all the other conditions (Table 1). The fact that the viewing distance was greater for the *Braced* and *Fixed* conditions means that the angular subtense of the digits to be read was smaller than when viewed from a shorter distance. Perhaps the angular subtense at the larger viewing distance was too small to allow the numbers to be read? This is not so. Even with the increased viewing distance, the digits were large enough to remain clearly visible to our participants who had normal, or corrected-to-normal, vision. Hence visual acuity limitations cannot explain the greater reduction in PRP for the *Braced* or *Fixed* conditions (Fig. 3a). Similarly, differences in accommodation demand between the *Braced* and *Fixed* conditions relative to the other conditions cannot explain the poorer PRP in these conditions. This is because the accommodative demand is less when the viewing distance is greater, and because the variation in accommodation demand was no greater for the *Braced* and *Fixed* conditions compared to the other conditions. In any case, the temporal responsiveness of the human accommodation system does not allow the accommodation to vary in real time as the distance between the phone and the user increases and decreases as part of the rhythmic walking pattern (Dubost et al. 2006). Thus, our results suggests that the poorer PRP in the *Braced* and *Fixed* conditions compared to other conditions was not due to the factors of accommodation or visual acuity but instead as a result of the increased variability in the phone's relative acceleration in the forward-back, up-down and right-left planes.

Our findings indicate that PRP in the *Slow* and *Cust* conditions was similar to that for the *Standing* condition even though the variability in the phone's relative acceleration was much higher in the *Slow* and *Cust* conditions compared to the *Standing* condition. This suggests that the visual system is resistant to some movement of the target being viewed. However, once this threshold in the phone's relative acceleration is exceeded, PRP is compromised, presumably because the retinal image becomes unstable. This threshold is unlikely to have a fixed/definitive value and will likely vary depending on the characteristics of the visual task. For example, if the stimulus (digit) size is decreased, a reduction in PRP from that achieved under static conditions (i.e., standing) might become evident even at slow walking speeds. Moreover, similar to the outcomes from the studies by Ludvigh and Miller (1958), Demer and Amjadi (1993) and Verbecque et al. (2018), the results of the present study indicate large inter-individual variations in PRP as walking speed increased. For example, Participant 5 was able to maintain the same PRP for the *Fast* condition as that achieved for the *Slow* (mean PRP for both conditions was 10.5 digits), while Participant 6's PRP for the *Fast* condition (mean 7.75 digits) was noticeably poorer than what was achieved for the *Slow* condition (mean 10.5 digits) (Online Resource 2). This highlights that some individuals demonstrate greater resistance to increases in phone relative acceleration, while others are more susceptible to acceleration increases. Future work should investigate whether certain population groups, e.g. older adults, those with vestibular disorders, and those with increased incidence of falling are more susceptible to acceleration increases, and whether such susceptibility predisposes them to having poorer visual control during walking and hence puts them at an increased risk of tripping or falling.

A key factor in any dynamic visual task is the input of the vestibulo-ocular reflex (VOR). This mechanism detects head motion and compensates via inducing eye movements in order to keep the retinal image as stable as possible (Grossman et al. 1989; Leigh and Zee 1999). Reduced performance of the VOR has been reported in otherwise healthy participants after concussion or head trauma, and is higher for those who have a history of falling (Mucha et al. 2014; Elbin et al. 2018). None of the participants in the current study reported a recent fall or dizziness, concussion or head trauma. However, it is possible that VOR performance differed between participants simply due to normal, inter-individual differences, and this inter-individual variation in VOR performance might help explain the considerable inter-subject variability in PRP we observed. Hence, future work that investigates how the act of walking affects phone reading performance, or indeed visual performance in any dynamic situation, should assess whether VOR or other eye movements likely to be involved in the task (e.g. pursuits), can explain the changes in performance that occur when an individual is in motion compared to when they are stationary.

Assessing changes in gaze angles without a gaze tracking device

In the present study, we presented a new approach for assessing where the gaze is directed that did not require the use of a gaze tracking device. Typically, identifying where the eyes are looking (i.e., where gaze is directed) is evaluated using an eye-tracking device. These devices are head-mounted which permits analysing the gaze angle relative to the head whilst the participant is in motion. The approach used in the present study was to measure the *assumed* gaze angle. By tracking movements of the phone screen relative to the head's reference axis with the origin located at the mid-point of the eyes, we assumed that motion of the screen relative to the head would mean there was a corresponding change in gaze angle. It is important to emphasise that measuring assumed gaze angle in this way can only be done for periods when it is known that the object being tracked (which in the current study was the phone) is actually being viewed. In the present study we knew participants had to be looking at the phone-screen during the period of the test because they were calling out the numbers presented on it. Determining the changes in assumed gaze angle in the up-down and right-left directions during the two second period when the phone was being viewed indicated the gaze requirements of the phone-reading task, i.e., it indicated where the eyes were assumed to be directed during this 2 second period. However, this is not necessarily where the gaze was actually directed to at any instant in time because changes in the actual gaze direction may have lagged behind, or moved ahead, of the instantaneous/changing position of the phone screen. We are planning to undertake work to determine how closely changes in assumed gaze angles match changes in the actual angle (direction) of gaze. If the angle of assumed gaze matches closely the actual angle of gaze, the approach we have used here will offer an advantage over using an eye tracking system because eye-trackers (typically consisting of some type of glasses/goggles) can be obtrusive; for example, they can interfere with the field of view, and can be difficult to use when the individual being assessed is wearing their habitual spectacle correction.

Limitations

We used a treadmill so as to provide a controlled set of walking speeds in order to determine the effect of changes in phone motion relative to the eyes on the ability to read numbers displayed on a phone. A limitation of using a treadmill is that it eliminates optic flow patterns (Patla 1997) that are present during normal, overground walking. The absence of optic flow information during treadmill walking may influence the ability to read a phone whilst walking and this impact might be different across different walking speeds. Therefore, future research should investigate whether the absence of optic flow in treadmill walking impacts upon phone reading ability. Another possible limitation of using a treadmill is that the head motion induced by walking on a treadmill may be different to the head motion induced when walking overground for the reasons we highlighted above. However, although there may be differences in the head motion for treadmill walking compared to overground walking, the findings in the current study indicating that PRP is reduced when motion of the phone relative to the eyes increases in irregularity, should be just as applicable to overground walking as to treadmill walking.

Summary & Conclusions

In summary, this study has demonstrated that, during walking, PRP is poorer when motion of the phone relative to the eyes becomes increasingly irregular. Irregular relative phone motion arose when walking speed was increased, and when the motion-coupling between the phone and the eyes was further disrupted using an arm brace or when the phone was not hand-held. Our findings suggest that whilst walking, the visual system displays some resistance to motion of the phone relative to the eyes but that considerable inter-individual differences exist in the level of such resistance, even amongst apparently visually-normal individuals. As the walking speed was increased or when the motion of the phone relative to the eyes was increased through the use of an arm brace or by not holding the phone in the hand, the visual system was unable to make the necessary eye movements and/or changes in accommodation quickly enough to stabilize and/or focus the retinal image of the irregularly moving phone so as to allow the information presented to be read. We believe these findings may explain why pedestrians slow their walking when viewing their phone. Specifically, walking slows because the head motion induced at slower speeds is smoother and more regular, which means it is easier to couple the motion of the hand-held phone to motion of the head. This coupling ensures that the retinal image of the information on the screen is stable enough to maintain visibility.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Alejandro Rubio Barañano. The first draft of the manuscript was written by Alejandro Rubio Barañano and John Buckley and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declarations

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Conflicts of interest: The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material: Phone reading performance data for every participant is included as Supplementary Material (see Online Resource 2).

Code availability: Not applicable.

Ethics approval: Approval was obtained from the ethics committee of the University of Bradford. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to participate: Informed consent was obtained from all individual participants included in the study.

Consent for publication: Patients signed informed consent regarding publishing their data.

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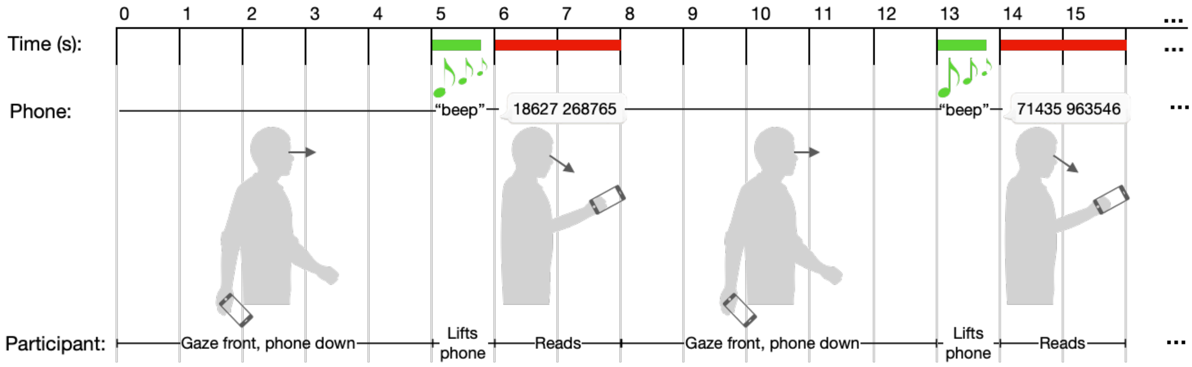

Figure 1. The phone reading task. Participants look to the front, holding the phone with arms by the side in relaxed position, as in normal walking. After hearing the "beep" from the phone, participants raise their arm, look at the screen, and begin reading aloud the sequence of numbers. The presentation disappears after 2 seconds, and participants look again to the front with arms relaxed (free to swing). 5 seconds later, the next reading trial commences until a total of 5 trials is completed in each block.

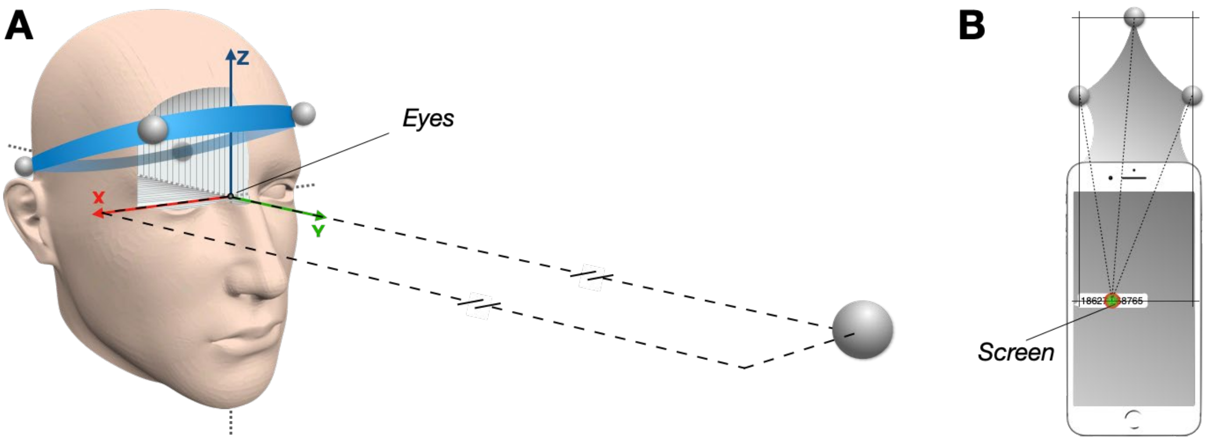

Figure 2. A: Static calibration. Defining the position of the *Eyes* and reference frame relative to the tracked "head" segment (headband), undertaken whilst participants stood still and looked to a marker placed at 1.5m in front of them. The marker was horizontally and vertically aligned with the midpoint of their eyes. **B**: Defining *Screen* position in relation to the markers attached to the "phone", Note *Screen* offset, from middle of screen, represents location of where text is displayed.

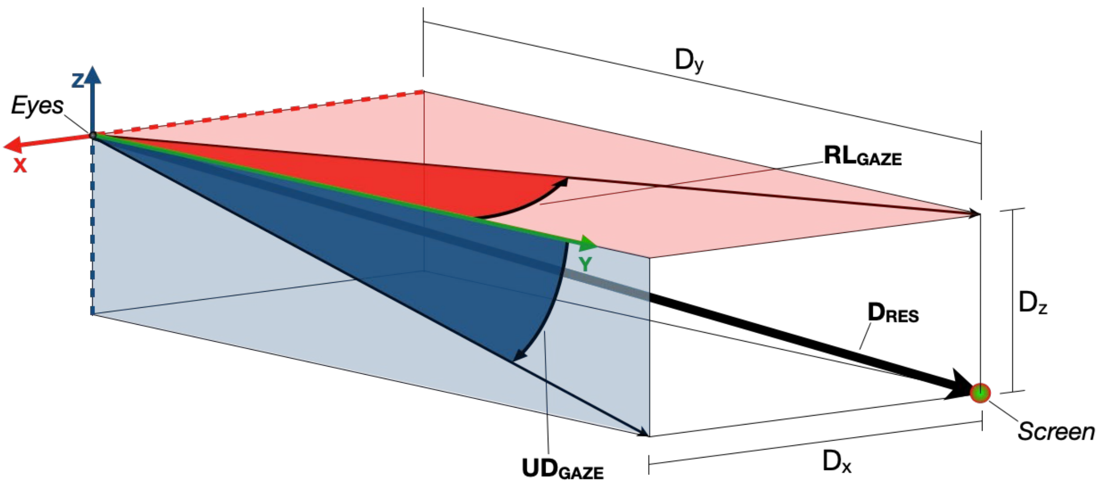

Figure 3. Kinematic outcome measures: D_{RES} is distance of the *Screen* from the *Eyes,* i.e., resultant displacement (D_x, D_y, D_z). UD_{GAZE} and RL_{GAZE} indicate gaze angles in the "*yz*" (up-down) and "*xy*" (left-right) planes, respectively, i.e., gaze angles relative to the head-segment's reference frame (indicated by red [x] and blue [z] planes). The example in the figure shows the *Screen* displaced downwards and leftwards from the neutral (static calibration) alignment, resulting in negative UD_{GAZE} and RL_{GAZE} angles.

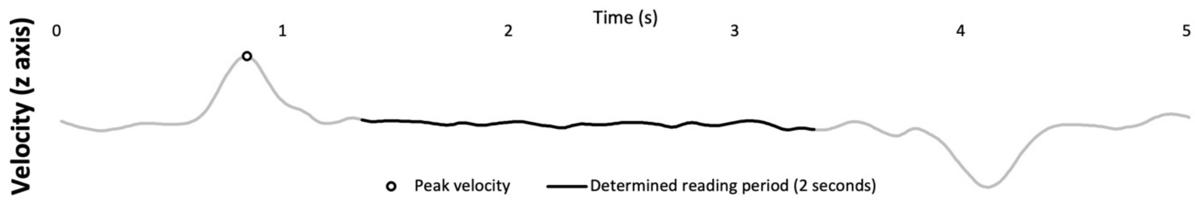

Figure 4. Determination of phone reading period: the beginning of each of the reading periods of 2 seconds was determined by finding the phone's peak velocity (relative to the head) in the *z* axis (vertical direction) and adding 50 milliseconds to the time at which peak velocity occurred.

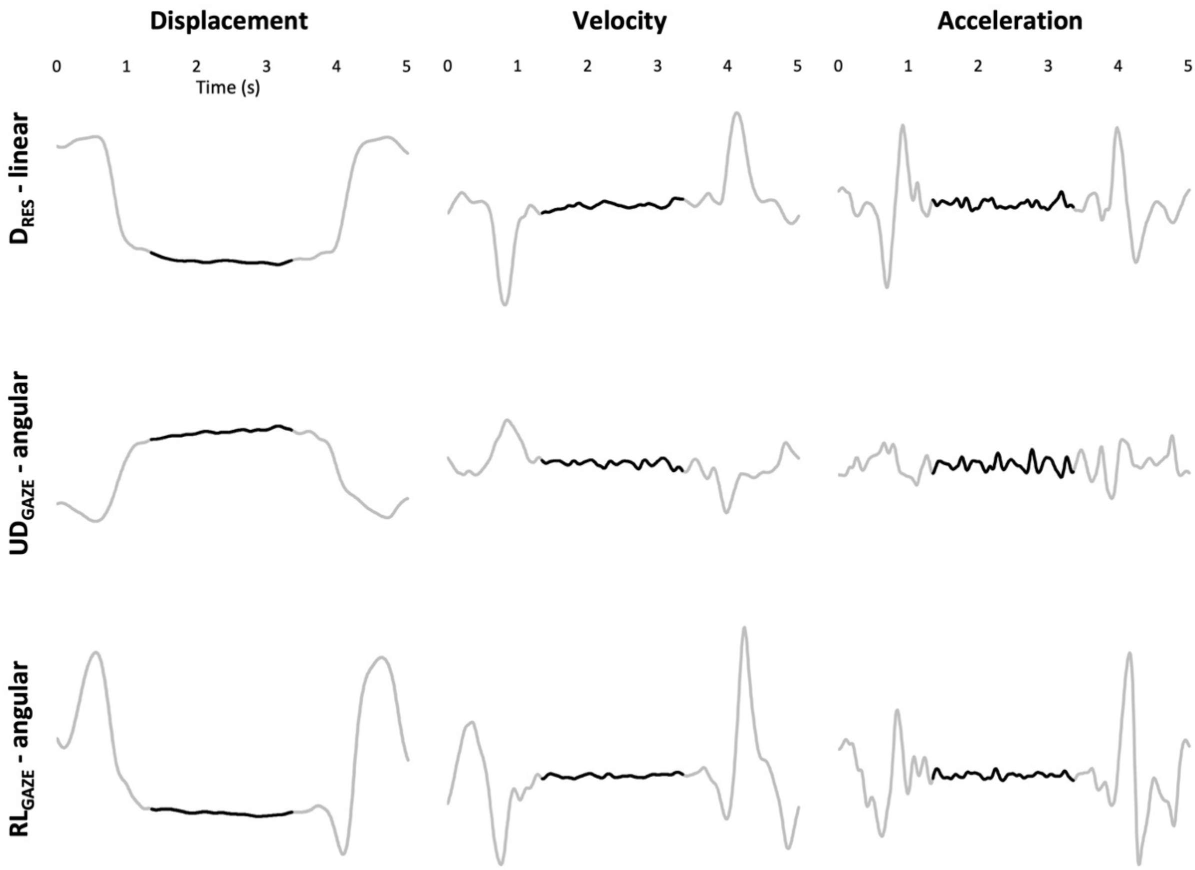

Figure 5. Exemplar data from one participant showing the phone's relative motion during a reading trial at customary speed. The black portion of line in each figure represents the 2 second 'stable' period, i.e., phone reading period. The outcome variables (D_{RES}_Acc-SD, UD_{GAZE}_Acc-SD and RL_{GAZE}_Acc-SD) were determined for this 'stable' period only. The left-hand panels show the linear and angular displacement of the phone relative to the eyes; D_{RES}, indicates the resultant, relative linear displacement, i.e., viewing distance, and UD_{GAZE} and RL_{GAZE}, indicate the relative angular displacement of the phone in the Up-Down and Right-Left directions respectively. The middle and right-hand panels show the associated velocities and accelerations, i.e., the first and second derivatives of the displacements are shown in the left-hand panels.

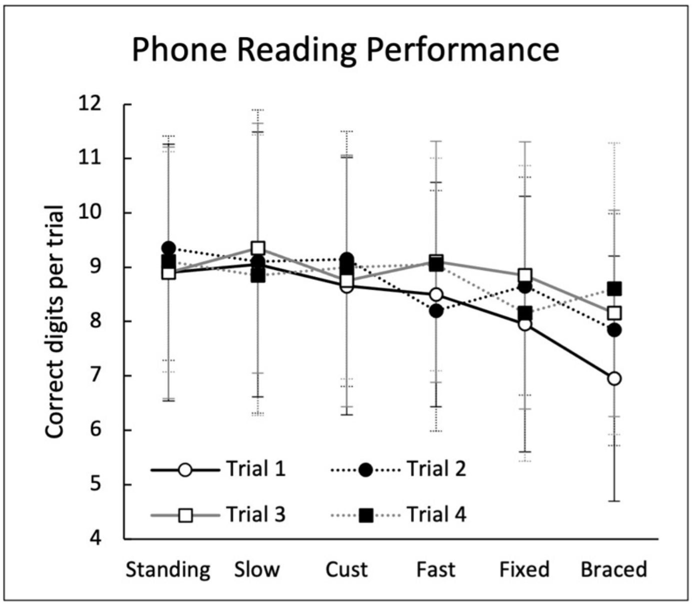

Figure 6. Group mean PRP for each trial and condition. Error bars represent the group SD for each condition and trial.

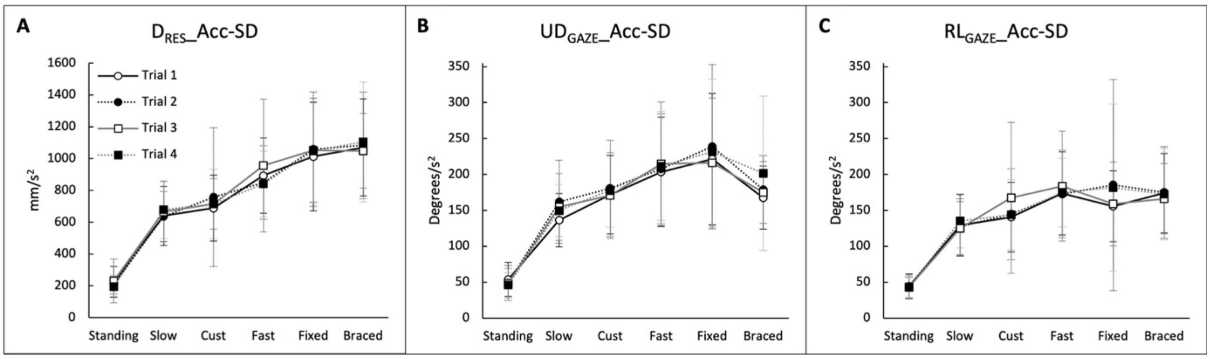

Figure 7. Group average variability in the phone's relative acceleration. **A**: D_{RES}_Acc-SD; **B**: UD_{GAZE}_Acc-SD; **C**: RL_{GAZE}_Acc-SD across testing conditions and trial repetitions. Error bars represent the group SD for each condition and trial.

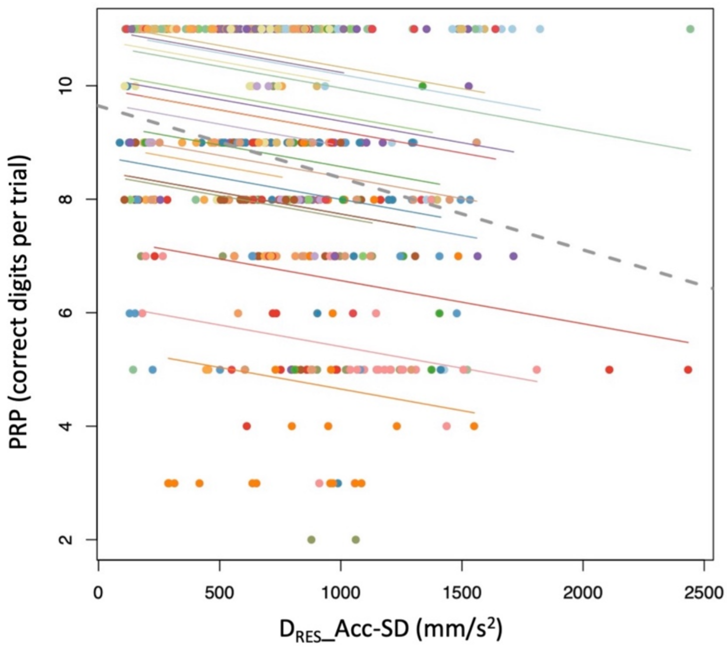

Figure 8. Repeated measures correlation between PRP and D_{RES}_Acc-SD. Different coloured dots and lines represent different participants. Thicker dotted grey line shows the adjusted r-value for the whole group ($r = -0.16$; $p < 0.0004$). Note that correlations between PRP and both UD_{GAZE}_Acc-SD and RL_{GAZE}_Acc-SD, showed a similar pattern but are not included here.

Table 1. Group mean (±SD) viewing distance (D_{RES}) and assumed gaze angles (UD_{Gaze} and RL_{Gaze}) across the six conditions.

Mean ± SD	**D_{RES} (cm)**	**UD_{GAZE} (deg)**	**RL_{GAZE} (deg)**	**D_{RES} Post-hoc**	**UD_{GAZE} Post-hoc**	**RL_{GAZE} Post-hoc**
Standing	33.1 ± 4.9	-10.7 ± 8.9	0.2 ± 12.7	Braced^{1}, Fixed^{1}	-	Braced^{3}
Slow	33.1 ± 4.8	-10.1 ± 7.9	-0.3 ± 13.5	Braced^{1}, Fixed^{1}	-	Braced^{2}
Cust	33.3 ± 5.3	-10.3 ± 8.6	0.9 ± 13.2	Braced^{1}, Fixed^{1}	-	Braced^{3}
Fast	33.3 ± 5	-10.4 ± 7.3	0.4 ± 13.7	Braced^{1}, Fixed^{1}	-	Braced^{3}
Braced	43.8 ± 5.2	-10.9 ± 10.1	3.6 ± 13.1	Fixed^{1}	-	-
Fixed	50.4 ± 9.2	-12.2 ± 8.5	1.2 ± 14.2	Braced^{1}	-	-

Walking speeds (mean ± SD) (m/s): slow = 0.92 ± 0.16; customary = 1.14 ± 0.20; fast = 1.49 ± 0.26.
^{1}: $p_{Holm}<0.001$; ^{2}: $p_{Holm}<0.01$; ^{3}: $p_{Holm}<0.05$

Supplementary Material

Methods:

How assumed gaze angles were determined

A stationary standing 'calibration' trial was recorded for each participant. Each participant stood still on the treadmill and was asked to look to a marker placed at 1.5m in front of them that was vertically and horizontally aligned with the midpoint of their eyes (*Eyes* virtual point). The head's reference frame was then relocated to the *Eyes* and then rotated to match the participant's neutral gaze orientation (Fig. S1), i.e., UD_{GAZE} and RL_{GAZE} angles were configured to be equal to zero when the participant was standing still with their head held in a neutral position and looking to the marker in front of them.

With the head's reference frame embedded at the *Eyes*, the output of the 3D motion tracking from the reading (dynamic) trials was converted from the lab-based coordinated system into the head's-reference coordinate system. In other words, the coordinate position (x,y,z) of the phone screen was determined relative to the *Eyes* position (see Fig. S2 for exemplar data).

The assumed gaze angle in the up-down and in the right-left directions were then determined as follows:

$$UD_{GAZE} = \tan^{-1}(D_z/D_y) \cdot (180/\pi)$$

$$RL_{GAZE} = \tan^{-1}(D_x/D_y) \cdot (180/\pi).$$

where Dx, Dy, and Dz indicate the relative phone displacement (in head's reference frame) in the X, Y, and Z directions, respectively.

The UD_{GAZE} and RL_{GAZE} angles represent the assumed orientation of gaze during the phone reading task. UD_{GAZE} and RL_{GAZE} angles are positive when the phone is located above or rightwards of a neutral head orientation, and they become negative when the phone is located below or leftwards of the neutral head orientation (see Fig. S3 for exemplar data).

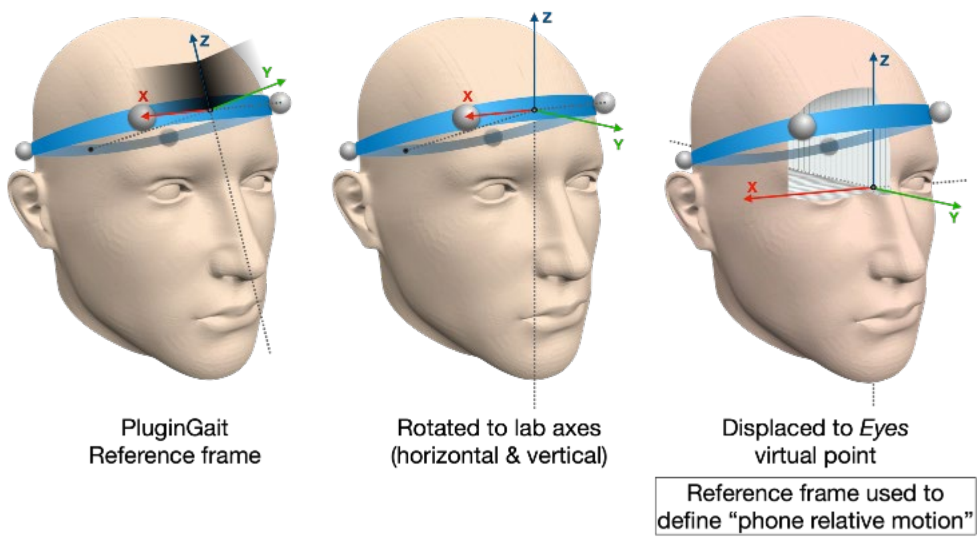

Fig. S1 Steps taken in relocating and reorienting the PluginGait head-reference frame to the *Eyes* virtual point.

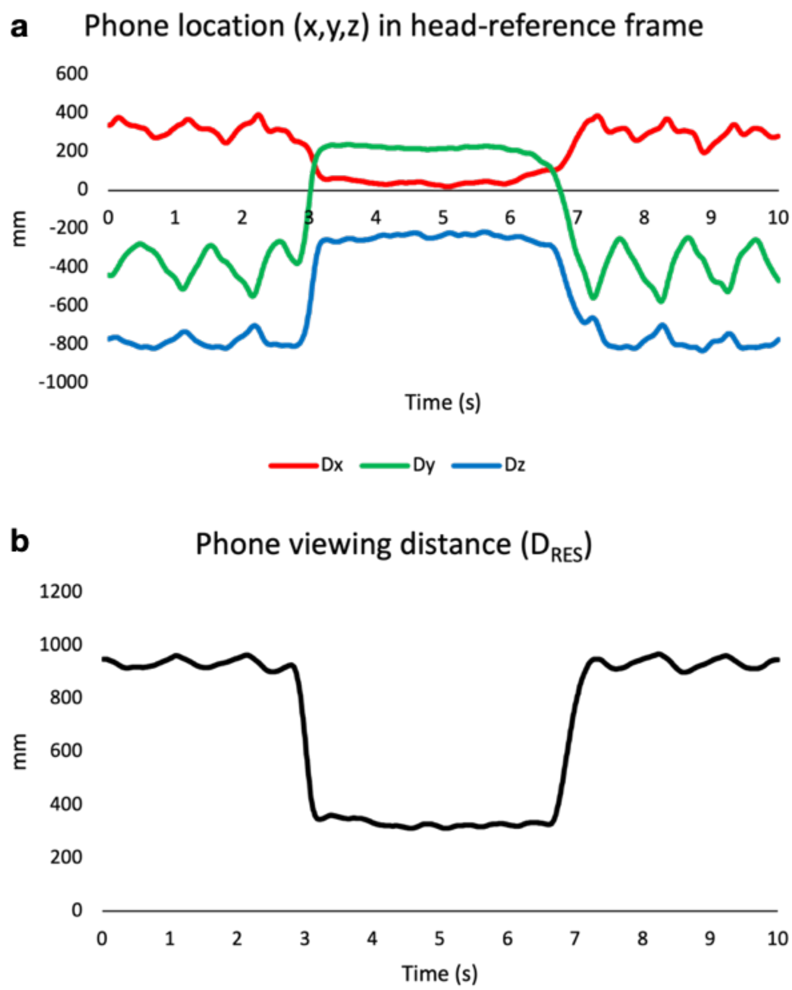

Fig. S2 a Exemplar data from one reading trial showing the x, y, z (mm) location of the phone screen in the head-reference frame (i.e., the *Screen* position relative to the *Eyes* position). NB., the negative ‘offset’ in Dy (~400mm) and Dz (~800mm) and positive ‘offset’ in Dx (~30mm) before and after the reading period, indicates the hand-held phone is, on average, behind, below and to the right of the *Eyes* position respectively when the arm holding the phone (right arm) swings freely. **b** From the x, y, z location of the phone-screen, the resulting scalar viewing distance (D_{RES}) was determined. For this exemplar reading trial the viewing distance was on average around 320mm.

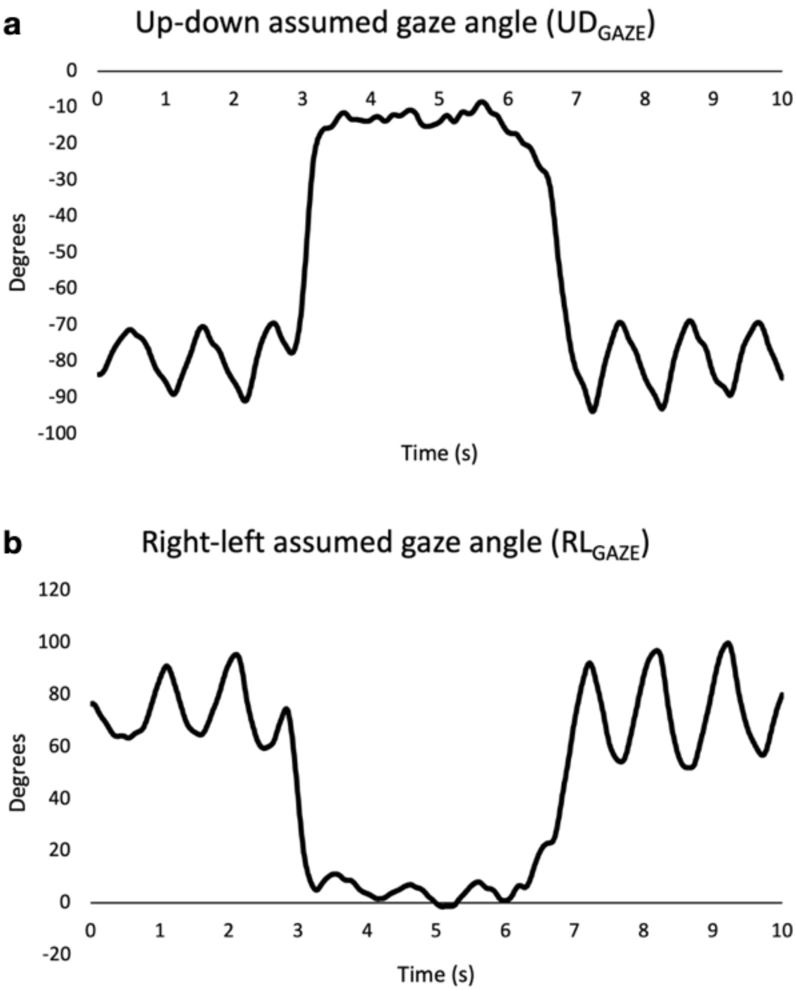

Fig. S3 a illustrates the assumed gaze angle in the up-down direction, and **b** illustrates the assumed gaze angle in the right-left direction. NB., during the reading period (period from 3.5-5.5 sec, for this exemplar trial) the UD$_{GAZE}$ angle approximates to around -15 degrees and the RL$_{GAZE}$ angle approximates to around 5 degrees. This is indicative of the head being orientated forwards and tilted slightly downwards with the phone being viewed slightly to the right of the head. The slight rightwards 'offset' in RL$_{GAZE}$ was because the phone was held in the participant's right hand. The downwards 'offset' in UD$_{GAZE}$ indicates the phone was being held at an average height that was below the neutral gaze orientation.

Results: auxiliary

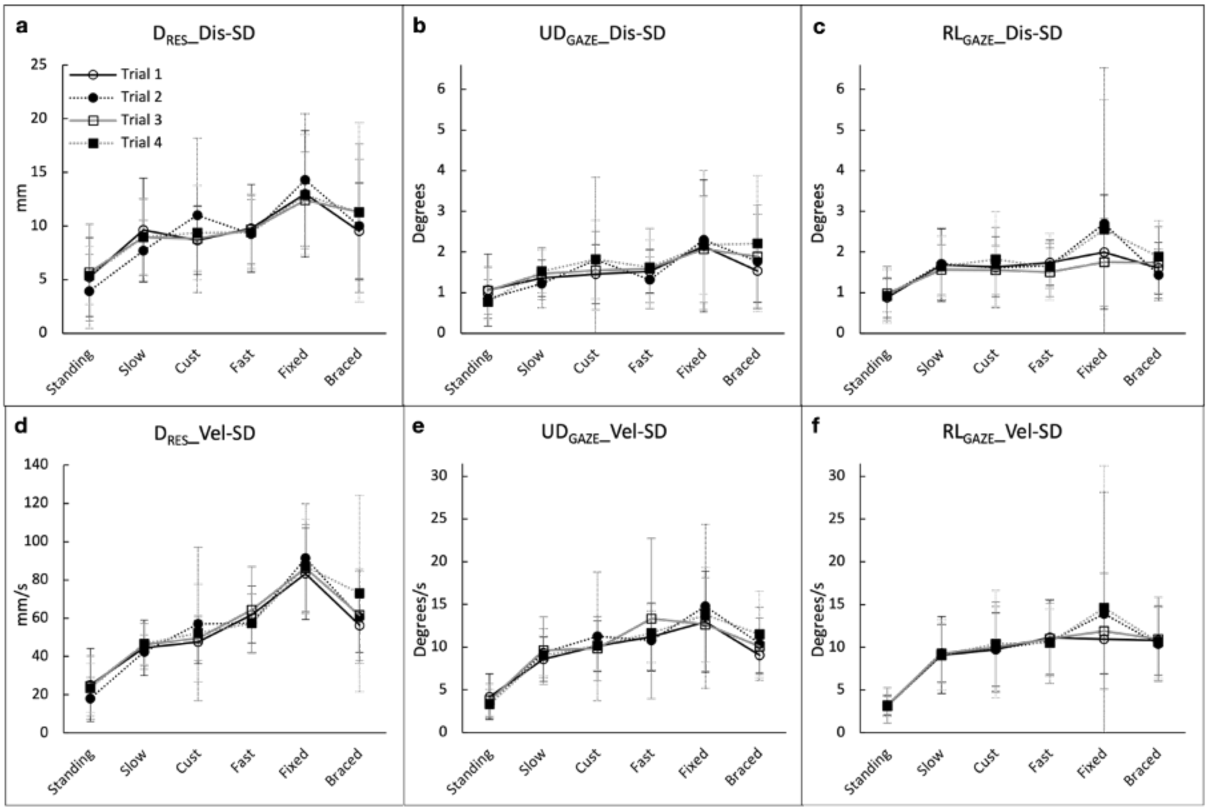

Fig. 4 Group average variability in the phone's relative displacement **a** D_{RES}_Dis-SD, **b** UD_{GAZE}_Dis-SD, **c** RL_{GAZE}_Dis-SD, and group average variability in the phone's relative velocity; **d** D_{RES}_Vel-SD, **e** UD_{GAZE}_Vel-SD, **f** RL_{GAZE}_Vel-SD, across testing conditions and trial repetitions. Error bars represent the group SD for each condition and trial.

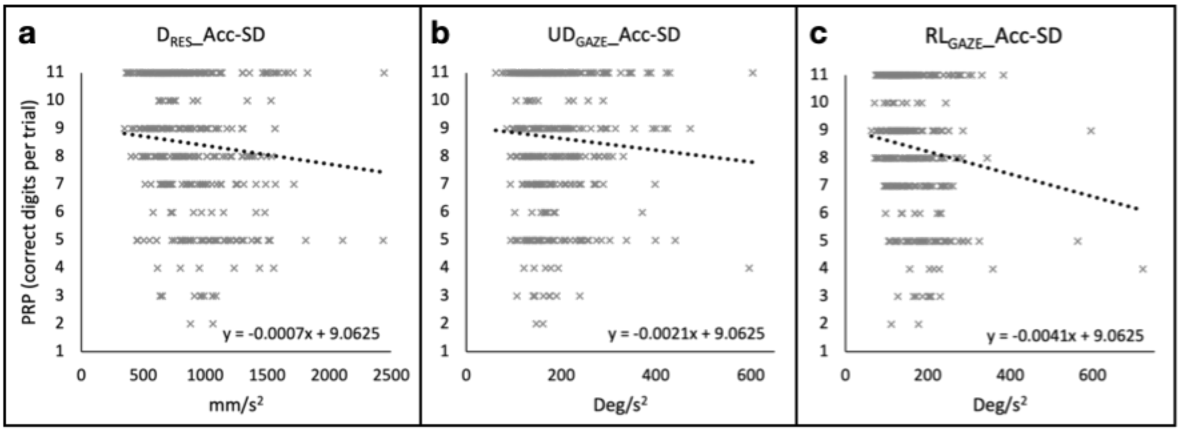

Fig. 5 Scatter (x,y) plots of **a** PRP and UD_{GAZE}_Acc-SD, and **b** PRP versus RL_{GAZE}_Acc-SD. The data plotted is the acceleration data collected from the walking conditions (i.e. data collected for the Standing condition were not included). In each plot, a linear regression model was used in which the regression line intercept ("c" value) was set as the group average PRP value determined for the standing condition (which was 9.06 digits read correctly in the two second time period).

Table 2 Database containing each participant's phone reading performance scores (see column PRP) for every condition and trial. PRP represents the number of phone-digits correctly read (out of 11) during the 2-second reading period.

P	C	T	PRP
1	S0	1	11
1	S0	2	11
1	S0	3	11
1	S0	4	11
1	HS	1	8
1	HS	2	11
1	HS	3	11
1	HS	4	11
1	HN	1	8
1	HN	2	11
1	HN	3	11
1	HN	4	11
1	HF	1	10
1	HF	2	11
1	HF	3	11
1	HF	4	11
1	SF	1	11
1	SF	2	11
1	SF	3	11
1	SF	4	11
1	BF	1	5
1	BF	2	8
1	BF	3	9
1	BF	4	11
2	S0	1	5
2	S0	2	6
2	S0	3	6
2	S0	4	8
2	HS	1	11
2	HS	2	11
2	HS	3	9
2	HS	4	5
2	HN	1	7
2	HN	2	7
2	HN	3	8
2	HN	4	7
2	HF	1	11
2	HF	2	5
2	HF	3	9
2	HF	4	7
2	SF	1	6
2	SF	2	9
2	SF	3	7
2	SF	4	8
2	BF	1	8
2	BF	2	11
2	BF	3	9
2	BF	4	8
3	S0	1	9
3	S0	2	9
3	S0	3	9
3	S0	4	10
3	HS	1	9
3	HS	2	8
3	HS	3	9
3	HS	4	9
3	HN	1	9
3	HN	2	9
3	HN	3	8
3	HN	4	9
3	HF	1	8
3	HF	2	9
3	HF	3	9
3	HF	4	9
3	SF	1	8
3	SF	2	8
3	SF	3	9
3	SF	4	5
3	BF	1	3
3	BF	2	9
3	BF	3	6
3	BF	4	7
4	S0	1	8
4	S0	2	11
4	S0	3	5
4	S0	4	11
4	HS	1	8
4	HS	2	11
4	HS	3	11
4	HS	4	11
4	HN	1	11
4	HN	2	11
4	HN	3	11
4	HN	4	11
4	HF	1	11
4	HF	2	11
4	HF	3	11
4	HF	4	11
4	SF	1	11
4	SF	2	11
4	SF	3	11
4	SF	4	8
4	BF	1	11
4	BF	2	5
4	BF	3	11
4	BF	4	11
5	S0	1	11
5	S0	2	9
5	S0	3	11
5	S0	4	8
5	HS	1	9
5	HS	2	11
5	HS	3	11
5	HS	4	11
5	HN	1	8
5	HN	2	11
5	HN	3	8
5	HN	4	11
5	HF	1	11
5	HF	2	9
5	HF	3	11
5	HF	4	11
5	SF	1	8
5	SF	2	8
5	SF	3	11
5	SF	4	8
5	BF	1	7
5	BF	2	8
5	BF	3	11
5	BF	4	11
6	S0	1	11
6	S0	2	11
6	S0	3	11
6	S0	4	9
6	HS	1	11
6	HS	2	11
6	HS	3	11
6	HS	4	9
6	HN	1	10
6	HN	2	11
6	HN	3	11
6	HN	4	11
6	HF	1	7
6	HF	2	8
6	HF	3	8
6	HF	4	8
6	SF	1	5
6	SF	2	8
6	SF	3	9
6	SF	4	5
6	BF	1	5
6	BF	2	7
6	BF	3	5
6	BF	4	6
7	S0	1	7
7	S0	2	9
7	S0	3	11
7	S0	4	9
7	HS	1	8
7	HS	2	11
7	HS	3	11
7	HS	4	11
7	HN	1	7
7	HN	2	7
7	HN	3	9
7	HN	4	11
7	HF	1	7
7	HF	2	5
7	HF	3	11
7	HF	4	10
7	SF	1	7
7	SF	2	7
7	SF	3	5
7	SF	4	2
7	BF	1	5
7	BF	2	9
7	BF	3	9
7	BF	4	2
8	S0	1	6
8	S0	2	8
8	S0	3	7
8	S0	4	7
8	HS	1	3
8	HS	2	3
8	HS	3	6
8	HS	4	5
8	HN	1	5
8	HN	2	5
8	HN	3	5
8	HN	4	5
8	HF	1	5
8	HF	2	8
8	HF	3	5
8	HF	4	5
8	SF	1	5
8	SF	2	5
8	SF	3	5
8	SF	4	7
8	BF	1	5
8	BF	2	5
8	BF	3	4
8	BF	4	5
9	S0	1	11
9	S0	2	11
9	S0	3	11
9	S0	4	11
9	HS	1	11
9	HS	2	11
9	HS	3	5
9	HS	4	7
9	HN	1	11
9	HN	2	11
9	HN	3	9
9	HN	4	8
9	HF	1	8
9	HF	2	11
9	HF	3	11
9	HF	4	11
9	SF	1	9
9	SF	2	9
9	SF	3	11
9	SF	4	6
9	BF	1	8
9	BF	2	5
9	BF	3	8
9	BF	4	11
10	S0	1	8
10	S0	2	8
10	S0	3	8
10	S0	4	7
10	HS	1	8
10	HS	2	6
10	HS	3	9
10	HS	4	8
10	HN	1	5
10	HN	2	5
10	HN	3	5
10	HN	4	7
10	HF	1	5
10	HF	2	4
10	HF	3	6
10	HF	4	9
10	SF	1	8
10	SF	2	8
10	SF	3	5
10	SF	4	9
10	BF	1	5
10	BF	2	5
10	BF	3	7
10	BF	4	5
11	S0	1	11
11	S0	2	11
11	S0	3	11
11	S0	4	11
11	HS	1	11
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11	HN	4	7
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11	HF	2	6
11	HF	3	11
11	HF	4	11
11	SF	1	11
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11	SF	3	9
11	SF	4	11
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11	BF	3	7
11	BF	4	11
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12	S0	2	11
12	S0	3	8
12	S0	4	11
12	HS	1	9
12	HS	2	11
12	HS	3	9
12	HS	4	5
12	HN	1	8
12	HN	2	9
12	HN	3	11
12	HN	4	8
12	HF	1	8
12	HF	2	7
12	HF	3	7
12	HF	4	9
12	SF	1	5
12	SF	2	8
12	SF	3	11
12	SF	4	11
12	BF	1	8
12	BF	2	10
12	BF	3	7
12	BF	4	7
13	S0	1	3
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13	SF	4	4
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13	BF	3	8
13	BF	4	9
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14	S0	2	9
14	S0	3	9
14	S0	4	8
14	HS	1	11
14	HS	2	5
14	HS	3	11
14	HS	4	9
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14	HN	3	11
14	HN	4	9
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14	HF	2	7
14	HF	3	7
14	HF	4	8
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14	SF	2	11
14	SF	3	8
14	SF	4	9
14	BF	1	5
14	BF	2	5
14	BF	3	7
14	BF	4	7
15	S0	1	11
15	S0	2	11
15	S0	3	9
15	S0	4	9
15	HS	1	8
15	HS	2	9
15	HS	3	8
15	HS	4	10
15	HN	1	8
15	HN	2	11
15	HN	3	9
15	HN	4	11
15	HF	1	11
15	HF	2	7
15	HF	3	11
15	HF	4	10
15	SF	1	8
15	SF	2	8
15	SF	3	11
15	SF	4	7
15	BF	1	8
15	BF	2	9
15	BF	3	9
15	BF	4	8
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16	S0	2	9
16	S0	3	8
16	S0	4	9
16	HS	1	9
16	HS	2	11
16	HS	3	11
16	HS	4	11
16	HN	1	11
16	HN	2	11
16	HN	3	5
16	HN	4	11
16	HF	1	9
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16	HF	3	9
16	HF	4	7
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16	SF	4	11
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16	BF	4	11
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17	S0	2	11
17	S0	3	11
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17	SF	2	11
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17	SF	4	11
17	BF	1	11
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17	BF	3	8
17	BF	4	11
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18	S0	3	10
18	S0	4	10
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18	BF	2	11
18	BF	3	9
18	BF	4	11
19	S0	1	11
19	S0	2	9
19	S0	3	11
19	S0	4	11
19	HS	1	11
19	HS	2	11
19	HS	3	11
19	HS	4	11
19	HN	1	11
19	HN	2	9
19	HN	3	11
19	HN	4	9
19	HF	1	11
19	HF	2	11
19	HF	3	11
19	HF	4	9
19	SF	1	8
19	SF	2	11
19	SF	3	11
19	SF	4	11
19	BF	1	11
19	BF	2	10
19	BF	3	11
19	BF	4	11
20	S0	1	8
20	S0	2	9
20	S0	3	8
20	S0	4	8
20	HS	1	11
20	HS	2	8
20	HS	3	9
20	HS	4	8
20	HN	1	9
20	HN	2	9
20	HN	3	7
20	HN	4	8
20	HF	1	7
20	HF	2	7
20	HF	3	5
20	HF	4	8
20	SF	1	7
20	SF	2	9
20	SF	3	8
20	SF	4	8
20	BF	1	7
20	BF	2	7
20	BF	3	8
20	BF	4	9

"P": Participant, "C": Condition, "T": Trial, "PRP": Phone Reading Performance, "S0": Standing, "HS": Slow, "HN": Normal, "HF": Fast, "SF": Fixed, "BF": Braced